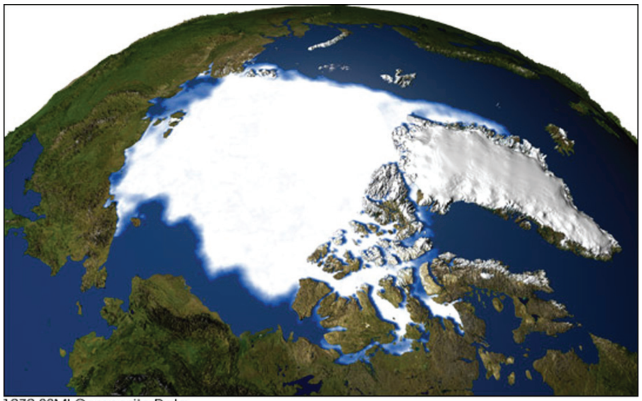
High-Resolution Arctic Sea Ice Modeling



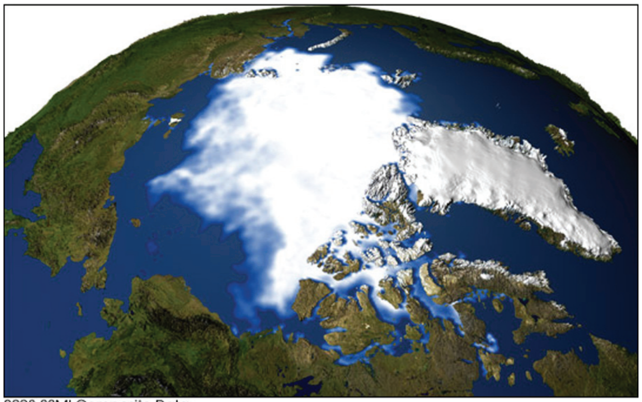


Figure 1: Composite images of sea ice in the Arctic region acquired by the Defense Meteorological Satellite Program Special Sensor Microwave Imager for 1979 (left) and 2003 (right). Source: earthobservatory.nasa.gov

Sandia is examining critical environmental parameters needed to accurately predict the behavior of sea ice due to global warming

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Climate change is having a disproportional impact in the Arctic due in part to complex positive feedback mechanisms involving the reflectivity and insulating properties of sea ice. As sea ice is lost, the underlying ocean is exposed to the atmosphere causing more solar radiation to be absorbed, which in turn causes further warming. The composite images of sea ice in the Arctic region shown in Figure 1 clearly demonstrate the retreat of sea ice from 1979 to 2003. Loss of sea ice facilitates recovery of previously inaccessible natural resources that may increase the possibility of international conflicts. Therefore, given the important role of sea ice in climate change and the geopolitical importance of the Arctic, high-fidelity sea ice simulations to support science-based policy making are essential.

The development and analysis of high-resolution sea ice models pose a number of serious modeling and simulation challenges. The codes used to predict the behavior of sea ice combine complex physical models for melting and growth due to radiative forcing as well as motion and deformation due to ocean current and wind forcing. The solutions can be affected by uncertainties in the forcing data, errors due to simplifications in the physical models, and errors resulting from the numerical solution methods. In conjunction with the Dept. of Energy's Office of Biological and Environmental Research Climate Research Project, Sandia researchers are addressing these sources of error by considering new physical models for the ice, developing improved numerical algorithms for their solution, and quantitatively evaluating the sensitivities of the models to input parameters.

Existing sea ice models are made up of dynamic and thermodynamic components that include a two-dimensional momentum equation for ice velocity, a constitutive model for ice internal forces, a one-dimensional heat equation for ice column temperature, and an evolution equation for ice thickness distribution. The LANL model CICE represents the state-of-the-art in sea ice modeling and has been designed to couple with the ocean and atmosphere components in the Community Climate System Model maintained by the National Center for Atmospheric Research. However, CICE has several limitations. First, the

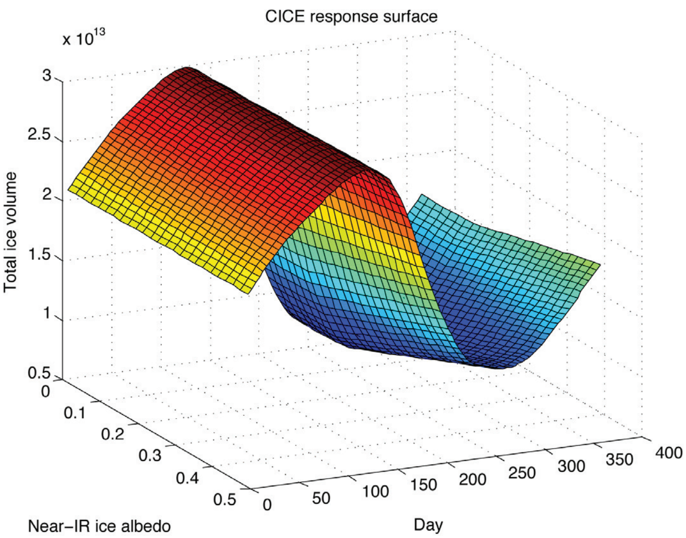

Figure 2: Single-parameter Dakota study performed with the LANL's CICE code. The response surface corresponds to the total ice volume as function of the near-IR ice albedo, and the day of the year.

constitutive model assumes that the response of ice to forcing is isotropic; this results in non-physical deformations for regions dominated by a large crack or other linear features. Second, the numerical methods used to solve the sea ice dynamics equations result in artificial diffusion and dispersion that cause smearing of the ice edge. Another approach, based on a code developed at the University of New Mexico, is designed to overcome these limitations by using an elastic-decohesive constitutive model solved with the Material-Point Method (MPM). It uses both Lagrangian particles to facilitate the discretization of the advection term in the dynamics equations and an anisotropic constitutive model that explicitly includes cracks.

Any predictive sea-ice model necessarily involves a large number of material and environmental parameters that are inherently uncertain. As a first step towards a quantitative characterization of the resulting simulation uncertainty, Sandia is evaluating the sensitivity of both the CICE and the MPM models with respect to these parameters. This allows researchers to rank the relative importance of different parameters for the propagation of uncertainties in a model and provide the means to reduce the dimension of the parameter space in an uncertainty quantification process. For this task, Arctic basin-wide simulations are being performed and the response of overall sea ice volume and area to parameters such as albedo, emissivity, and density are being evaluated. These sensitivity analyses rely on Sandia's DAKOTA (Design Analysis Kit for Optimization) sampling tools and leverage the laboratory's significant knowledge base in uncertainty quantification. A typical response surface obtained by a single-parameter DAKOTA study using the CICE model is shown in Figure 2. In this example, the surface corresponds to the total ice volume in the Arctic region plotted as function of the near-Infra-Red (IR) ice albedo, and the day of the year. The study reveals a weakly nonlinear response for albedo values between 0.0 and 0.15, followed by a transition to a linear response for values between 0.15 and 0.5. Comparison of the ice thickness plots for near IR ice albedo of 0.1 and 0.5, shown in Fig. 3, demonstrates substantial qualitative differences caused by the variation in this parameter. Similar DAKOTA studies are underway for the MPM model. Comparison of the sensitivities of the two sea ice models will help to increase confidence in their predictive capabilities and improve our understanding of the complex interactions between various parameters.

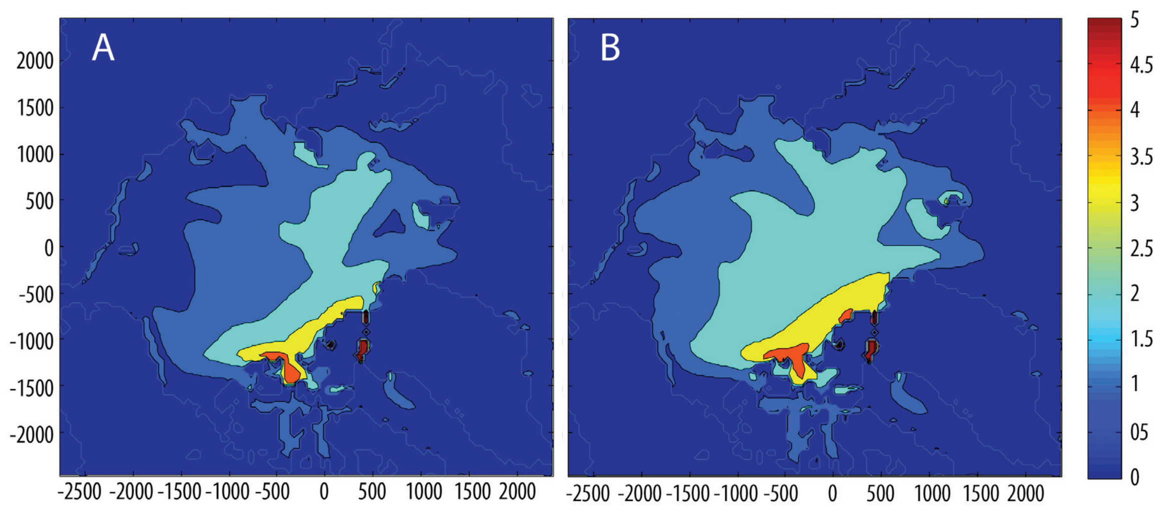

Figure 3: Dependence of sea ice thickness (meters) on near-IR ice albedo. (A) Ice thickness for high levels of near-IR absorption (near-IR ice albedo of 0.1). (B) Ice thickness for low levels of near-IR absorption (near-IR ice albedo of 0.5).